

## 1 WHAT IS CLAIMED IS:

2 1. An audio processor, comprising:  
3 a virtualizer operable to process audio information to  
4 virtualize at least one speaker so that, from a listener's  
5 perspective, sounds appear to come from at least one direction  
6 where a physical speaker is not present; and  
7 a controller operable to configure the virtualizer, wherein  
8 the virtualizer can be configured to virtualize the at least one  
9 speaker at any location in a space around the listener.

1 2. The audio processor of Claim 1, wherein the virtualizer  
2 comprises:

3 a filter operable to filter input signals comprising the audio  
4 information;

5 a forward crossover path operable to receive, delay, and  
6 filter an output of the filter;

7 a first combiner operable to produce first output signals for  
8 a first physical speaker using the output of the filter;

9 a second combiner operable to produce second output signals  
10 for a second physical speaker using an output of the forward  
11 crossover path;

12 a first feedback crossover path operable to receive, delay,  
13 and filter the first output signals, the second combiner further

14 operable to produce the second output signals using an output of  
15 the first feedback crossover path; and

16 a second feedback crossover path operable to receive, delay,  
17 and filter the second output signals, the first combiner further  
18 operable to produce the first output signals using an output of the  
19 second feedback crossover path.

1 3. The audio processor of Claim 1, wherein the virtualizer  
2 comprises:

3 a plurality of filters operable to filter a plurality of input  
4 signals, the input signals comprising at least a portion of the  
5 audio information;

6 a plurality of forward crossover paths each operable to  
7 receive, delay, and filter an output from one of the filters;

8 one or more first combiners operable to produce first output  
9 signals for a first physical speaker using an output from at least  
10 one of the forward crossover paths and the output from at least one  
11 of the filters;

12 one or more second combiners operable to produce second output  
13 signals for a second physical speaker using an output from at least  
14 one other of the forward crossover paths and the output from at  
15 least one other of the filters;

16 a first feedback crossover path operable to receive, delay,

17 and filter the first output signals, the one or more second  
18 combiners further operable to produce the second output signals  
19 using an output from the first feedback crossover path; and  
20 a second feedback crossover path operable to receive, delay,  
21 and filter the second output signals, the one or more first  
22 combiners further operable to produce the first output signals  
23 using an output from the second feedback crossover path.

1 4. The audio processor of Claim 3, wherein:

2 the one or more first combiners are further operable to  
3 produce the first output signals using first unfiltered input  
4 signals; and

5 the one or more second combiners are further operable to  
6 produce the second output signals using second unfiltered input  
7 signals.

1 5. The audio processor of Claim 4, further comprising an  
2 attenuator operable to attenuate third unfiltered input signals;

3 wherein the one or more first combiners are further operable  
4 to produce the first output signals using the attenuated third  
5 input signals; and

6 wherein the one or more second combiners are further operable  
7 to produce the second output signals using the attenuated third  
8 input signals.

1           6.    The audio processor of Claim 3, further comprising a  
2    plurality of additional filters each operable to filter one of  
3    first, second, and third additional input signals;

4           wherein the one or more first combiners are further operable  
5    to produce the first output signals using the filtered first  
6    additional input signals and the filtered third additional input  
7    signals; and

8           wherein the one or more second combiners are further operable  
9    to produce the second output signals using the filtered second  
10   additional input signals and the filtered third additional input  
11   signals.

1           7.    The audio processor of Claim 1, wherein:

2           the virtualizer comprises at least one first filter, one or  
3    more forward crossover paths each comprising a first delay line and  
4    a second filter, and two feedback crossover paths each comprising a  
5    second delay line and a third filter; and

6           the controller is operable to configure the virtualizer by  
7    altering a frequency response of one or more of the filters and a  
8    delay of one or more of the delay lines.

8. The audio processor of Claim 1, wherein:

the virtualizer comprises at least one first filter, one or more forward crossover paths each comprising a first delay line and a second filter, and two feedback crossover paths each comprising a second delay line and a third filter;

at least one first filter has a frequency response  $P$  of

$$|P| = \left| \frac{H_i(\phi)}{H_i(\theta)} \right|,$$

at least one second filter has a frequency response  $F$  of

$$|F| = \left| \frac{H_c(\phi)}{H_i(\phi)} \right|,$$

at least one third filter has a frequency response  $F_T$  of

$$|F_T| = \left| \frac{H_c(\theta)}{H_i(\theta)} \right|,$$

at least one first delay line provides a delay  $D$  of

$$D = t(\phi) - t(F), \text{ and}$$

at least one second delay line provides a delay  $D_T$  of

$$D_T = t(\theta) - t(F_T),$$

wherein  $\theta$  represents an angle associated with at least one physical speaker,  $\phi$  represents an angle associated with at least one virtualized speaker,  $H_i$  represents a transfer function associated with one of the listener's ears,  $H_c$  represents a transfer function associated with another of the listener's ears,

21  $t(\phi)$  represents an inter-time difference associated with the at  
 22 least one virtualized speaker,  $t(\theta)$  represents an inter-time  
 23 difference associated with the at least one physical speaker,  $t(F)$   
 24 represents a delay associated with at least one second filter, and  
 25  $t(F_T)$  represents a delay associated with at least one third filter.

1 9. The audio processor of Claim 1, wherein:

2 the virtualizer comprises two first filters, two forward  
 3 crossover paths each comprising a first delay line and a second  
 4 filter, and two feedback crossover paths each comprising a second  
 5 delay line and a third filter;

6 at least one first filter has a frequency response  $P_s$  of

$$7 \quad |P_s| = \left| \frac{H_i(\phi)}{H_i(\theta)} \right|,$$

8 at least one second filter has a frequency response  $F_s$  of

$$9 \quad |F_s| = \left| \frac{H_c(\phi)}{H_i(\phi)} \right|,$$

10 at least one third filter has a frequency response  $F_T$  of

$$11 \quad |F_T| = \left| \frac{H_c(\theta)}{H_i(\theta)} \right|,$$

12 at least one first delay line provides a delay  $D_s$  of  
 13  $D_s = t(\phi) - t(F_s)$ , and

14 at least one second delay line provides a delay  $D_T$  of

15  $D_T = t(\theta) - t(F_T),$

16 wherein  $\theta$  represents an angle associated with two physical  
 17 speakers,  $\phi$  represents an angle associated with two virtualized  
 18 speakers,  $H_i$  represents a transfer function associated with one of  
 19 the listener's ears,  $H_c$  represents a transfer function associated  
 20 with another of the listener's ears,  $t(\phi)$  represents an inter-time  
 21 difference associated with the two virtualized speakers,  $t(\theta)$   
 22 represents an inter-time difference associated with the two  
 23 physical speakers,  $t(F_S)$  represents a delay associated with at  
 24 least one second filter, and  $t(F_T)$  represents a delay associated  
 25 with at least one third filter.

1 10. The audio processor of Claim 1, wherein:

2 the virtualizer comprises a first filter, two second filters,  
 3 and two third filters, two first forward crossover paths each  
 4 comprising a first delay line and a fourth filter, two second  
 5 forward crossover paths each comprising a second delay line and a  
 6 fifth filter, and two feedback crossover paths each comprising a  
 7 third delay line and a sixth filter;

8 at least one first filter has a frequency response  $P_c$  of

9  $|P_c| = \left| \frac{H_i(0^\circ)}{H_i(\theta)} \right|,$

10 at least one second filter has a frequency response  $P_f$  of

$$|P_F| = \left| \frac{H_i(\omega)}{H_i(\theta)} \right|,$$

at least one third filter has a frequency response  $P_S$  of

$$|P_S| = \left| \frac{H_i(\phi)}{H_i(\theta)} \right|,$$

at least one fourth filter has a frequency response  $F_F$  of

$$|F_F| = \left| \frac{H_c(\omega)}{H_i(\omega)} \right|,$$

at least one fifth filter has a frequency response  $F_S$  of

$$|F_S| = \left| \frac{H_c(\phi)}{H_i(\phi)} \right|,$$

at least one sixth filter has a frequency response  $F_T$  of

$$|F_T| = \left| \frac{H_c(\theta)}{H_i(\theta)} \right|,$$

at least one first delay line provides a delay  $D_F$  of

$$D_F = t(\omega) - t(F_F),$$

at least one second delay line provides a delay  $D_S$  of

$$D_S = t(\phi) - t(F_S), \text{ and}$$

at least one third delay line provides a delay  $D_T$  of

$$D_T = t(\theta) - t(F_T),$$

wherein  $\theta$  represents an angle associated with two physical speakers,  $\phi$  represents an angle associated with two first virtualized speakers,  $\omega$  represents an angle associated with two



29 second virtualized speakers,  $H_i$  represents a transfer function  
30 associated with one of the listener's ears,  $H_c$  represents a  
31 transfer function associated with another of the listener's ears,  
32  $t(\phi)$  represents an inter-time difference associated with the two  
33 first virtualized speakers,  $t(\omega)$  represents an inter-time  
34 difference associated with the two second virtualized speakers,  
35  $t(\theta)$  represents an inter-time difference associated with the two  
36 physical speakers,  $t(F_F)$  represents a delay associated with at  
37 least one fourth filter,  $t(F_S)$  represents a delay associated with  
38 at least one fifth filter, and  $t(F_T)$  represents a delay associated  
39 with at least one sixth filter.

1        11. A device, comprising:

2        an audio source operable to provide audio information; and

3        an audio processor operable to receive the audio information

4 and process the audio information to virtualize at least one

5 speaker so that, from a listener's perspective, sounds appear to

6 come from at least one direction where a physical speaker is not

7 present, the audio processor being configurable to virtualize the

8 at least one speaker at any location in a space around the

9 listener.

1        12. The device of Claim 11, wherein the audio processor

2 comprises:

3        one or more filters operable to filter one or more input

4 signals comprising at least a portion of the audio information;

5        one or more forward crossover paths each operable to receive,

6 delay, and filter an output from one of the filters;

7        one or more first combiners operable to produce first output

8 signals for a first physical speaker using one or more of: one or

9 more of the input signals, one or more outputs from the filters,

10 and one or more outputs from the forward crossover paths;

11        one or more second combiners operable to produce second output

12 signals for a second physical speaker using one or more of: one or

13 more of the input signals, one or more outputs from the filters,

14 and one or more outputs from the forward crossover paths;  
15 a first feedback crossover path operable to receive, delay,  
16 and filter the first output signals, the one or more second  
17 combiners further operable to produce the second output signals  
18 using an output from the first feedback crossover path; and  
19 a second feedback crossover path operable to receive, delay,  
20 and filter the second output signals, the one or more first  
21 combiners further operable to produce the first output signals  
22 using an output from the second feedback crossover path.

1 13. The device of Claim 12, further comprising an attenuator  
2 operable to attenuate additional input signals;

3 wherein the one or more first combiners are further operable  
4 to produce the first output signals using the attenuated input  
5 signals; and

6 wherein the one or more second combiners are further operable  
7 to produce the second output signals using the attenuated input  
8 signals.

1 14. The device of Claim 12, wherein:

2 each forward crossover path comprises a first delay line and a  
3 second filter;

4 each feedback crossover path comprises a second delay line and  
5 a third filter; and

6       the audio processor is configured by altering a frequency  
7       response of one or more of the filters and a delay of one or more  
8       of the delay lines.

1       15. The device of Claim 11, wherein the audio processor is  
2       operable to virtualize five speakers using two physical speakers.

1       16. The device of Claim 11, wherein the audio source  
2       comprises at least one of a television tuner, a radio tuner, a CD  
3       reader, and a DVD reader.

1       17. The device of Claim 11, wherein the audio source  
2       comprises an audio/video source operable to provide both audio and  
3       video information; and

4       further comprising a video processor operable to process the  
5       video information.

1        18. An apparatus for virtualizing a speaker at a location in  
2 space, comprising:

3        one or more filters operable to filter one or more input  
4 signals comprising audio information;

5        one or more forward crossover paths each operable to receive,  
6 delay, and filter an output from one of the filters;

7        one or more first combiners operable to produce first output  
8 signals for a first physical speaker using one or more of: one or  
9 more of the input signals, one or more outputs from the filters,  
10 and one or more outputs from the forward crossover paths;

11       one or more second combiners operable to produce second output  
12 signals for a second physical speaker using one or more of: one or  
13 more of the input signals, one or more outputs from the filters,  
14 and one or more outputs from the forward crossover paths;

15       a first feedback crossover path operable to receive, delay,  
16 and filter the first output signals, the one or more second  
17 combiners further operable to produce the second output signals  
18 using an output from the first feedback crossover path; and

19       a second feedback crossover path operable to receive, delay,  
20 and filter the second output signals, the one or more first  
21 combiners further operable to produce the first output signals  
22 using an output from the second feedback crossover path.

1        19. The apparatus of Claim 18, further comprising an  
2 attenuator operable to attenuate additional input signals;

3        wherein the one or more first combiners are further operable  
4 to produce the first output signals using the attenuated input  
5 signals; and

6        wherein the one or more second combiners are further operable  
7 to produce the second output signals using the attenuated input  
8 signals.

1        20. The apparatus of Claim 18, wherein:

2        each forward crossover path comprises a first delay line and a  
3 second filter;

4        each feedback crossover path comprises a second delay line and  
5 a third filter; and

6        the apparatus is configured by altering a frequency response  
7 of one or more of the filters and a delay of one or more of the  
8 delay lines.

1        21. The apparatus of Claim 18, further comprising a  
2 controller operable to configure the apparatus.

1           22. The apparatus of Claim 21, wherein the controller is  
2 operable to configure the apparatus based at least partially on  
3 locations of two or more physical speakers and locations of the  
4 speakers being virtualized.

1           23. The apparatus of Claim 18, wherein the audio processor is  
2 operable to virtualize five speakers using two physical speakers,  
3 the five virtualized speakers comprising a center speaker, two  
4 frontal speakers, and two surround sound speakers.

24. The apparatus of Claim 18, wherein:

the one or more filters comprise at least one first filter;

the one or more forward crossover paths each comprises a first delay line and a second filter;

the feedback crossover paths each comprises a second delay line and a third filter;

at least one first filter has a frequency response  $P$  of

$$|P| = \left| \frac{H_i(\phi)}{H_i(\theta)} \right|,$$

at least one second filter has a frequency response  $F$  of

$$|F| = \left| \frac{H_c(\phi)}{H_i(\phi)} \right|,$$

at least one third filter has a frequency response  $F_T$  of

$$|F_T| = \left| \frac{H_c(\theta)}{H_i(\theta)} \right|,$$

at least one first delay line provides a delay  $D$  of

$$D = t(\phi) - t(F), \text{ and}$$

at least one second delay line provides a delay  $D_T$  of

$$D_T = t(\theta) - t(F_T),$$

wherein  $\theta$  represents an angle associated with at least one physical speaker,  $\phi$  represents an angle associated with at least one virtualized speaker,  $H_i$  represents a transfer function associated with one of the listener's ears,  $H_c$  represents a



21 transfer function associated with another of the listener's ears,  
 22  $t(\phi)$  represents an inter-time difference associated with the at  
 23 least one virtualized speaker,  $t(\theta)$  represents an inter-time  
 24 difference associated with the at least one physical speaker,  $t(F)$   
 25 represents a delay associated with at least one second filter, and  
 26  $t(F_T)$  represents a delay associated with at least one third filter.

1 25. The apparatus of Claim 18, wherein:

2 the one or more filters comprise two first filters;

3 the one or more forward crossover paths comprise two forward  
 4 crossover paths each comprising a first delay line and a second  
 5 filter;

6 the feedback crossover paths each comprises a second delay  
 7 line and a third filter;

8 at least one first filter has a frequency response  $P_s$  of

$$9 \quad |P_s| = \left| \frac{H_i(\phi)}{H_i(\theta)} \right|,$$

10 at least one second filter has a frequency response  $F_s$  of

$$11 \quad |F_s| = \left| \frac{H_c(\phi)}{H_i(\phi)} \right|,$$

12 at least one third filter has a frequency response  $F_T$  of

$$13 \quad |F_T| = \left| \frac{H_c(\theta)}{H_i(\theta)} \right|,$$

14 at least one first delay line provides a delay  $D_s$  of

15  $D_s = t(\phi) - t(F_s)$ , and

16 at least one second delay line provides a delay  $D_T$  of

17  $D_T = t(\theta) - t(F_T)$ ,

18 wherein  $\theta$  represents an angle associated with two physical  
19 speakers,  $\phi$  represents an angle associated with two virtualized  
20 speakers,  $H_i$  represents a transfer function associated with one of  
21 the listener's ears,  $H_c$  represents a transfer function associated  
22 with another of the listener's ears,  $t(\phi)$  represents an inter-time  
23 difference associated with the two virtualized speakers,  $t(\theta)$   
24 represents an inter-time difference associated with the two  
25 physical speakers,  $t(F_s)$  represents a delay associated with at  
26 least one second filter, and  $t(F_T)$  represents a delay associated  
27 with at least one third filter.

1 26. The apparatus of Claim 18, wherein:

2 the one or more filters comprise a first filter, two second  
3 filters, and two third filters;

4 the one or more forward crossover paths comprise two first  
5 forward crossover paths each comprising a first delay line and a  
6 fourth filter and two second forward crossover paths each  
7 comprising a second delay line and a fifth filter;

8 the feedback crossover paths each comprises a second delay  
9 line and a sixth filter;

10 at least one first filter has a frequency response  $P_C$  of

$$11 \quad |P_C| = \left| \frac{H_i(0^\circ)}{H_i(\theta)} \right|,$$

12 at least one second filter has a frequency response  $P_F$  of

$$13 \quad |P_F| = \left| \frac{H_i(\omega)}{H_i(\theta)} \right|,$$

14 at least one third filter has a frequency response  $P_S$  of

$$15 \quad |P_S| = \left| \frac{H_i(\phi)}{H_i(\theta)} \right|,$$

16 at least one fourth filter has a frequency response  $F_F$  of

$$17 \quad |F_F| = \left| \frac{H_c(\omega)}{H_i(\omega)} \right|,$$

18 at least one fifth filter has a frequency response  $F_S$  of

$$19 \quad |F_S| = \left| \frac{H_c(\phi)}{H_i(\phi)} \right|,$$

20 at least one sixth filter has a frequency response  $F_T$  of

$$21 \quad |F_T| = \left| \frac{H_c(\theta)}{H_i(\theta)} \right|,$$

22 at least one first delay line provides a delay  $D_F$  of

$$23 \quad D_F = t(\omega) - t(F_F),$$

24 at least one second delay line provides a delay  $D_S$  of

$$25 \quad D_S = t(\phi) - t(F_S), \text{ and}$$

26 at least one third delay line provides a delay  $D_T$  of

27  $D_T = t(\theta) - t(F_T),$

28        wherein  $\theta$  represents an angle associated with two physical  
29 speakers,  $\phi$  represents an angle associated with two first  
30 virtualized speakers,  $\omega$  represents an angle associated with two  
31 second virtualized speakers,  $H_i$  represents a transfer function  
32 associated with one of the listener's ears,  $H_c$  represents a  
33 transfer function associated with another of the listener's ears,  
34  $t(\phi)$  represents an inter-time difference associated with the two  
35 first virtualized speakers,  $t(\omega)$  represents an inter-time  
36 difference associated with the two second virtualized speakers,  
37  $t(\theta)$  represents an inter-time difference associated with the two  
38 physical speakers,  $t(F_F)$  represents a delay associated with at  
39 least one fourth filter,  $t(F_S)$  represents a delay associated with  
40 at least one fifth filter, and  $t(F_T)$  represents a delay associated  
41 with at least one sixth filter.

1        27. A method, comprising:  
2        generating first output signals for a first physical speaker;  
3        and  
4        generating second output signals for a second physical  
5        speaker;  
6        wherein the first output signals emulate effects of a virtual  
7        speaker on one ear of a listener, the second output signals emulate  
8        effects of the virtual speaker on another ear of the listener, and  
9        each of the output signals at least partially cancels crosstalk  
10       caused by the other output signals.

1        28. The method of Claim 27, wherein generating the first and  
2        second output signals comprises:  
3        filtering one or more input signals to produce one or more  
4        filtered input signals;  
5        providing one or more of the filtered input signals to one or  
6        more forward crossover paths; and  
7        generating the first and second output signals using one or  
8        more of: one or more of the input signals, one or more of the  
9        filtered input signals, and one or more outputs from the forward  
10       crossover paths.

1        29. The method of Claim 28, further comprising:

2        providing the second output signals to a first feedback  
3 crossover path operable to receive, delay, and filter the second  
4 output signals; and

5        providing the first output signals to a second feedback  
6 crossover path operable to receive, delay, and filter the first  
7 output signals;

8        wherein generating the first output signals further comprises  
9 using an output from the second feedback crossover path; and

10       wherein generating the second output signals further comprises  
11 using an output from the first feedback crossover path.

1       30. The method of Claim 27, wherein the first and second  
2 output signals emulate the effects of multiple virtual speakers on  
3 the ears of the listener.

1       31. The method of Claim 27, wherein the first and second  
2 output signals emulate the effects of multiple virtual speakers at  
3 any locations in a space around the listener.

1       32. The method of Claim 31, wherein:

2       the first and second output signals are produced using one or  
3 more first filters, one or more forward crossover paths each  
4 comprising a first delay line and a second filter, and two feedback

5 crossover paths each comprising a second delay line and a third  
6 filter; and

7 further comprising altering a frequency response of one or  
8 more of the filters and a delay of one or more of the delay lines  
9 to change the location of one or more of the virtualized speakers.